A photoelectric polarimeter for XEUS: a new window in x-ray sky

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ABSTRACT

XEUS is a large area telescope aiming to rise X-ray Astronomy to the level of Optical Astronomy in terms of collecting areas. It will be based on two satellites, locked on a formation flight, one with the optics, one with the focal plane. The present design of the focal plane foresees, as an auxiliary instrument, the inclusion of a Polarimeter based on a Micropattern Chamber. We show how such a device is capable to solve open problems on many classes of High Energy Astrophysics objects and to use X-ray sources as a laboratory for a substantial progress on Fundamental Physics.

Keywords: X-Ray Astronomy, Polarimetry, Telescope, Detectors

1. INTRODUCTION

If we look back to the history of X-ray Astronomy we can say that after the first pioneering activity with rockets the sequence UHURU, Einstein, Chandra, following a path tracked by R. Giacconi, has been the backbone of this activity, that nowadays has arrived to a turning point. No major mission is presently established and ideas about how such a mission should be designed are not clear. Chandra has shown the great capabilities of an optics at sub-arcsecond level. Both Chandra and Newton have opened the window of high resolution spectroscopy. In some sense these two missions have brought X-ray Astronomy much closer to Optical Astronomy, but when we convert the effective areas of these telescopes into equivalent diameters we see that from the collection capability, they are equivalent to medium level optical amatorial telescopes, although equipped with an extremely performing focal plane instrumentations.

These rose the need of a new generation telescope with a collecting area two orders of magnitude higher, while still preserving an angular resolution at arcsecond level, which is imperative to study crowded deep fields avoiding source confusion. The availability of International Space Station suggested that such a telescope could be assembled in orbit, so bypassing the limits of launch vehicles. The fog that is folding the future of ISS and the general decline of funds for Space based Astronomical Research, have suggested a less ambitious solution. The present design is based on a telescope of completely new technology, drastically reducing the weight to area ratio, with an effective area of the order of 5 m^2 and a focal length of 35 m, harbored on one satellite. A second satellite will be launched with a complex focal plane instrumentation locked to the first in a formation flight. The ensemble should be put in a L2 orbit.

The focal plane would be based on two major instruments, a micro-calorimeter array based on TES technology and a Wide Field Imager based on APS technology. These two instruments will be the drivers for the study

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of remote Universe, explore the formation of large scale structures, the role of black holes and their interaction with galaxies. But they will provide as well the capability to study deep Physics of more bright objects. To this purpose the XEUS team is foreseeing the possibility to include more instrumentations, mainly devoted to a more restrict population of objects, but capable to address questions of extreme interest. These auxiliary instrumentations to be implemented if compatible with available resources and on the basis of a trade-off of the science, include a photoelectric polarimeter named XPOL.

2. X-RAY POLARIMETRY

2.1. Generalities

In Optical Astronomy polarimetry is somehow a niche discipline. In X-ray Astronomy it is expected to be a major topic for various reasons:

- The non thermal emission processes, such as synchrotron, cyclotron and non thermal bremsstrahlung play a significant role. They result in highly polarized radiation. X-ray polarimetry can enlighten the nature of the emission.
- The transfer of radiation from the emitting region to the observer undergo various processes that can result into a relevant polarization.

    1. In compact objects the radiation is scattered by regions whose geometry is far from spherical symmetry, including accretion disks and accretion columns. The selection of scattering angle in the direction of the observer result in a polarization, according to the Compton/Thomson cross sections. The scattering can modify the spectrum if the region is at high temperature or simply remove a part of photons which are photoabsorbed. This last process of scattering is usually named *reflection* and is marked by the presence of Fe K fluorescence photons (obviously unpolarized).
    2. In the presence of very high magnetic fields the radiation can be polarized by the combined effect of differential cross sections for the scattering of normal and anomalous modes in the plasma and vacuum birefringence, as predicted by Quantum Electrodynamics.
    3. In extended objects with thermal collisional equilibrium, such as clusters of galaxies, if the plasma is thin for the continuum and thick for resonance lines, the angle of last scattering in the direction of the observer will be selective and different in each part of the cluster resulting in a angular dependent polarization of the line photons.
    4. If some theories of Quantum Gravity based on the violation of the Lorentz invariance are true the vacuum is birefringent and the plane of polarization of photons should rotate of an amount that increases with energy and with distance. The detection of this effect would be of the highest interest. X-ray polarimetry can perform this test at highest energies and on long distance base by measuring the (expected) polarization of BL Lac objects and GRB afterglows on the Gpc scale.

    More in general a vast literature, distributed on almost 40 years, has made many predictions of the expected polarization from most of classes of X-ray sources. Yet the only positive detection has been, until now, that of Crab Nebula, first with a rocket then with OSO-8 satellite. This is one of the brightest sources in the x-ray sky, while many of the predictions refer to sources much fainter.

2.2. Technicalities

The statistics for a counting rate polarimeter applies also to the Micro Pattern Gas Detector at the focus of an X-ray optics. The relevant statistical quantity is the Minimum Detectable Polarization (MDP) which is the level of rejection of the hypothesis of absence of polarization with a confidence level of 99 % :

$$\mathrm{MDP} = \frac{4.29}{\mu S} \left(\frac{S+B}{T}\right)^{0.5}$$

where S is the source counting rate, B is the background, T the observing time and μ is the modulation factor which is defined as

$$\mu = \frac{C_{max} - C_{min}}{C_{max} + C_{min}}$$

for a 100 % polarized X-ray source, where C is the counting rate of the photoelectrons emitted in an a given angle-bin.

3. SCIENCE WITH XEUS

XEUS (X-Ray Evolving Universe Spectroscopy) it will be proposed as one of the major Missions to be included in the ESA Cosmic Vision 2015-2025. If approved it could be the only large X-ray telescope for many decades. Unavoidably, in this case, it will be used as a multi-purpose observatory, to cover any observations, in the X-ray band, of a certain level of interest. But the design of the mission is based on choices which find their rationale in a selected cluster of hot topics of Astrophysics and Fundamental Physics that can be addressed with data from an X-ray observation. The Major Goals of XEUS Mission are:

- Evolution of Large Scale Structure and Nucleosynthesis.
- Formation, dynamical and chemical evolution of groups and clusters.
- Baryonic composition of the Intergalactic Medium.
- Enrichment dynamics: inflows, outflows and mergers.
- Coeval Growth of Galaxies and Supermassive Black Holes.
- Birth and Growth of Supermassive Black Holes.
- Supermassive Black Hole induced galaxy evolution.
- Matter under Extreme Conditions.
- Gravity in the strong field limit.
- Equations of state.
- Acceleration phenomena.

These topics will be attacked with the primary instruments (NFI and WFI). The addition of a Polarimeter can significatively improve the science in some of these topics and add a few more. Therefore it is now foreseen as an auxiliary instrument, to be included compatibly with the tough technical constraints of such an ambitious mission.

4. POLARIMETRY FOR XEUS: CAPABILITIES AND CRITICALITIES

With XEUS optics X-ray polarimetry can be performed on celestial sources with fluxes down to fraction of mCrab up to Crab level. Very low MDP can in principle be reached with sources of very large fluxes. The FOV of XPOL, included a fiducial region determined by the extension of the tracks, is large enough to include the principal X-ray features of the Crab Nebula and to map most of the plerions with few pointings. Being capable to sustain large fluxes, good control of systematic effects permits to exploit at best the potentiality of the polarimeter. Photoelectric polarimetry and the modern concept of a subdivided detector permits to overcome most of the potential systematic effects connected with the use of the classical techniques in space such as non-uniformities in the Berillium window or in the analyzer. In this case, the analyzer (and the detector) is the gas itself which is intrinsically isotropic. The use of CMOS ASIC chip further permits to maintain the control of systematic below 1 % and at level not yet reached by laboratory measurement. A measurement which control the level of systematic effects can be accomplished by exploiting the internal calibration facility of the chip and with the possible use of an unpolarized low-activity Fe^{55} removable X-ray source. Background non-uniformities could be less important in L2 orbit with respect to Low Earth orbit. However they can be monitored exploiting the large field of view of XPOL, during the observation, selecting different regions of the detector outside the fiducial region containing the source in observation.

4.1. Data flow

The data managing for XPOL will take into account of the source rate under study. The requirements on the storage memory on board and on the time required to download the data will therefore remain limited. XPOL gather information from the GEM (Energy and time) and from the ASIC chip (coordinates of the frame vertex and energy and coordinates of the pixel in the frame). With the high throughput of XEUS we will compress data on-board (zero-suppression) by excluding the pixels with zero charge in further storage/download. Ad example for a crab-like spectrum the average rate of pixels before the zero-suppression is 630 pixel/event/s, after the zero-suppression the average rate of pixel/events/s becomes 24.5. For sources with fluxes above 10 mCrab we implement an on-board analysis which reconstruct the absorption point and photoelectron emission angle both based on well known simple algorithms. The event will be tagged with those information together with a quality parameter factor. For the Crab the expected bit rate is in this case 3.3 Mbit/s.

5. THE MPGC

The Micro Pattern Gas Detector[1,2,3] was first developed in 2001, with technology based on multilayer printed circuit board (PCB) with vias which brought the signals from the readout plane, patterned with hexagonal pixels 260 μm pitch, to the readout electronics. A Gas Electron Multiplier performs the multiplication of the charge produced by the photoelectrons tracks created in the drift/absorption region. The PCB technique limited the number of channels (1000-2000) and the pitch of the pixels (100-200 μm). Also long path to bring the signals were capacitatively coupled one to each other. The jump in the number of channels (hence in the coverage area and the FOV) and the decreasing in the pixel pitch (hence in the response to lower energy and the eventual use at high pressure) was it possible by designing and building an ASIC CMOS multilayer chip. The top metal layer is patterned in an honeycomb hexagonal pattern which is the readout plane of the charge produced by the photoelectrons. Each pixel is connected to a full electronics chain (pre-amplifier, shaping amplifier, sample and hold, multiplexer) built immediately below it, exploiting the remaining five layers of the VLSI CMOS technology. Three generations of chips have been developed so far with increasing area and throughput. The first VLSI CMOS chip (chip I) having 4 mm diameter, 2101 pixel chip and 80 μ pitch, was provided with external trigger and downloading of all the frame pixels with a rate capability of about 1 kHz. The second generation of chips, squared 1.1 cm x 1.1 cm (chip II), was patterned with 22000 pixels organized in 8 independent sub-frames of 2700 pixels with external or internal trigger. The frames can be readout in parallel providing a frame rate of 1-2 kHz. The third, and current generation of chip (chip III) is provided with unique characteristics to be used with the best performances for X-ray polarimetry.

5.1. The 105600 pixel chip and the Monte Carlo simulation.

The chip, which performances are described in detail in 4 has 105600 hexagonal pixels arranged at 50 μm pitch in a honeycomb matrix, corresponding to an active area of 15×15 mm^2. Each pixel (as the precedent generations) is connected to a charge-sensitive amplifier followed by a shaping circuit and a sample and hold-multiplexer circuit. The chip is organized in 16 identical clusters of 6600 pixels or alternatively in 8 clusters of 13200 pixels each one with an independent differential analog output buffer. In this last generation however each cluster has a customizable internal self-triggering capability with independently adjustable thresholds. Every 4 pixels contribute to a local trigger with a dedicated amplifier. The chip is capable to select for each event the rectangular region of interest (ROI) containing the track. This reduces the time of readout and the rate can be as high as 20 kHz. Also the noise is very low, 50 e$^-$/pixel, therefore the single electron readout is possible also with a small GEM gain.

Monte Carlo simulations have been developed on the base of well established functions that describe the interactions of electrons in ambient media and which are specialized for low energy applications and for gas mixtures. The simulations include the generation of ‘s’ and ‘p’ photoelectrons with the correct weight and initial angular distribution derived from the interaction of a polarized and unpolarized X-ray photon with the atoms of the gas. The performance for different configurations at different gas mixtures and pressure and thickness as a function of energy can be studied therefore in detail. The configuration adopted for XEUS is conservative. Micro Pattern Gas Detector with thickness of 1 cm, which provides negligible blurring of the image at the focus of the converging beam from the 35 m focal length mirror optics, and pressure of 1 atmosphere are currently in use in our laboratory.

6. THE DETECTOR FOR XPOL

Hereafter we show the main configuration properties for the detector XPOL shown in fig. 1 which basically consists of a well established technology gas cell with a charge multiplier coupled with a modern ASIC VLSI chip.

Since it provides simultaneously imaging, spectra and polarization, Micro Pattern Gas Detector could be the long sought laking tool for X-ray astronomy. Nowadays the use of CMOS VLSI chip permits to reach field of view of 1.5' x 1.5' at the focus of 35m XEUS optics therefore bringing XPOL already at the same level of throughout of the other instruments.

Table 1. Main characteristic of XPOL. In parenthesis are shown the resolution of the optics which drive the overall position resolution.

Position Resolution (FWHM, Linear)	150 μm (900 μm)
Position Resolution (FWHM, Angular)	0.88" (5")
Field of View (Linear)	1.5 cm $\times$ 1.5 cm
Field of View (Angular)	1.5' $\times$ 1.5'
Maximum Asynchr. Readout	10-20 kHz
FWHM @ 6 keV	15%
Timing accuracy	2 μs

6.1. Gas Cell

The gas cell is designed to include:

- A beryllium window 50μm thick.
- A set of field forming rings.
- A frame supporting the GEM.
- The VLSI chip described in section 5.1.
- Feed-through to carry bias voltages to the various internal components.
- A ceramic case to contain the gas.
- A ceramic base to mount the chip and route outside the signals and controls for the chip.

6.2. Gas Mixture

We do not discuss in detail the choice of the optimal filling mixture for the detector that will be object of further investigations. Off the recipe book of mixtures simulated so far we select the mixture He (40%) DME (60%) that seems well tuned to the present baseline design of the XEUS telescope and has the significant advantage of having been already tested with excellent results, coherent with what predicted by the Monte Carlo simulations. This makes the predictions we show in the next paragraphs as realistic as compatible with such an ambitious experiment. We stress, anyway, that this is far from any fix choice and a large room of improvement is there.

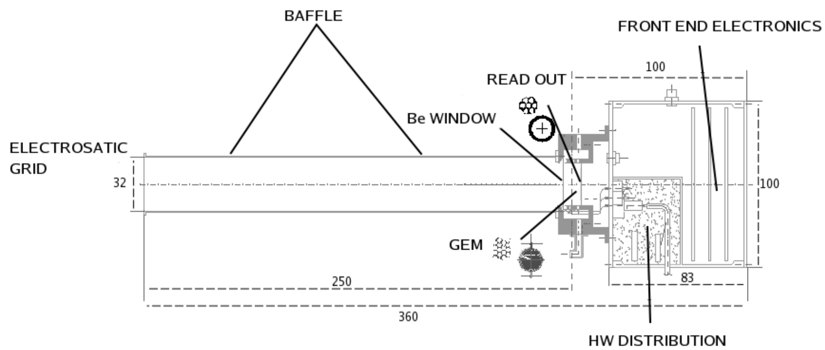


Figure 1. Design of the X-ray Polarimeter which includes the baffle to limit the field of view of XPOL by the mirror optics aperture and prevent diffuse X-ray background coming from the space which separates the two spacecraft modules to interact with the detector of XPOL (quotes are in mm).

7. XPOL PERFORMANCE

7.1. Efficiency and Modulation factor

Being a focal plane imaging instrument filled with low-Z gas (DME, He or Ne) XPOL has an intrinsic very low background.[5] Working down to 1.5-2 keV, in a large energy band, it overcomes the limits of the traditional approach of scattering polarimeter, which are insensitive below 5 keV and are background limited, and of Bragg crystal polarimeter, which work in a narrow band around the order of diffraction. The sensitivity of XPOL, therefore, is mostly dominated by the source flux down to very low values, therefore the sensitivity at a certain energy is proportional to the product $\epsilon^{0.5} \times \mu$ where ϵ is the efficiency of the gas mixture and μ is the modulation factor above defined. This is the quality factor of the polarimeter which drives the choice of the main physical parameter such as the drift region, the gas mixture and pressure. The choice of a gas mixture defines the energy band in which the X-ray polarimeter operates. We present here the compared quality factors for 1-cm 1-Atm for low atomic number mixtures. The result shows, basically, that the mixtures based on He-DME, which is currently proposed for the polarimeter on XEUS, better exploits the high effective area of the mirror at low energy. Nevertheless the polarimetric response at higher energies aimed to study the physics of the scattering privilege Neon-based mixtures. For now we consider the tested mixture (He 40 %-DME 60 %) which assures the better overall performance in terms of Minimum Detectable Polarization. From the simulations results that already an improvement at higher energies without loosing sensitivity at low energy derives from an increasing of the percentage of DME (see fig. 2).

7.2. Interface Electronics

The interface electronics (see fig. 3) will be capable to perform the following functions:

- Configure the ASIC CMOS.
- Process the data from the Gas Electron Multiplier.
- AD convert the pixel energy content.
- Store the pixel in the memory and perform the zero-suppression.
- Organize the event data structure.

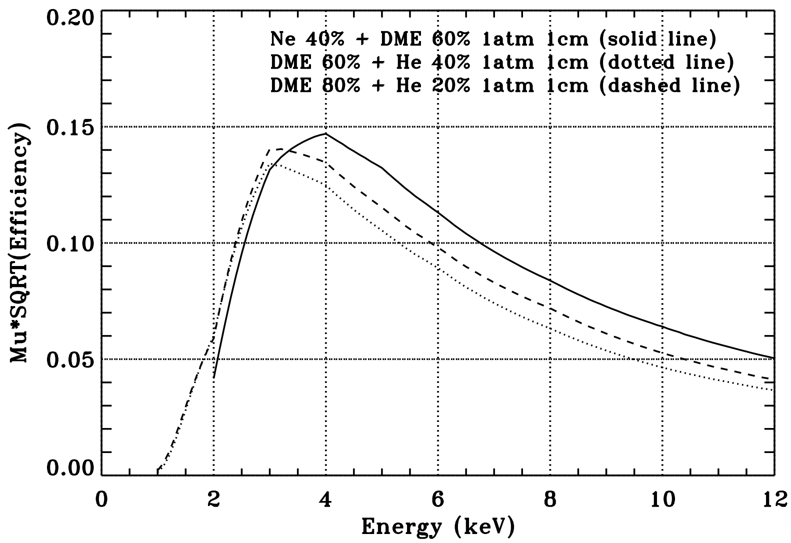


Figure 2. Quality factor derived from simulations for three tested mixture to be possibly used with XPOL on-board XEUS. He-DME mixtures provides the better polarimetric response to the XEUS optics while a Ne-DME mixture permits a better performance at the higher energy end.

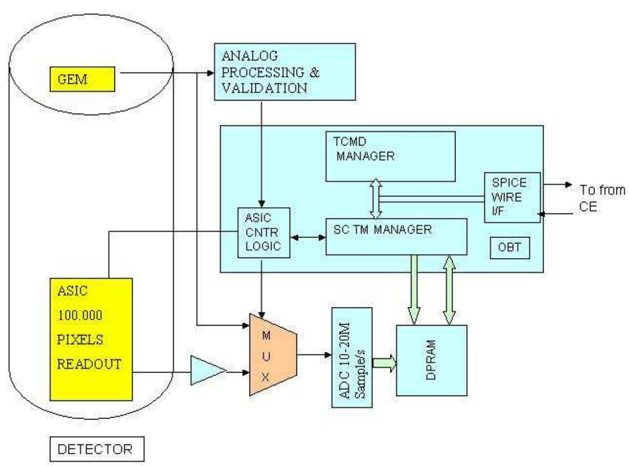


Figure 3. The Interface electronics and the Data Handling will be capable to manage the high troughput data from XEUS

Table 2. Weight volumes and power consumption for XPOL. FEE is the Front-End electronics, CE is the control Electronics which manage the telecommand to configure the chip, provide the mass memory to store the data and provide the power for the FEE and the Micro Pattern Gas Detector.

Unit	Mass (Kg)	Power (W)	Dimension (cm)
Detector + Baffle	2.0	3.5	28 × 6 Ø
FEE	1.5	3.5	10 × 8 × 10
CE	7.5	10	27 × 15 × 20
Total	11.0	17.0	10 × 8 × 10

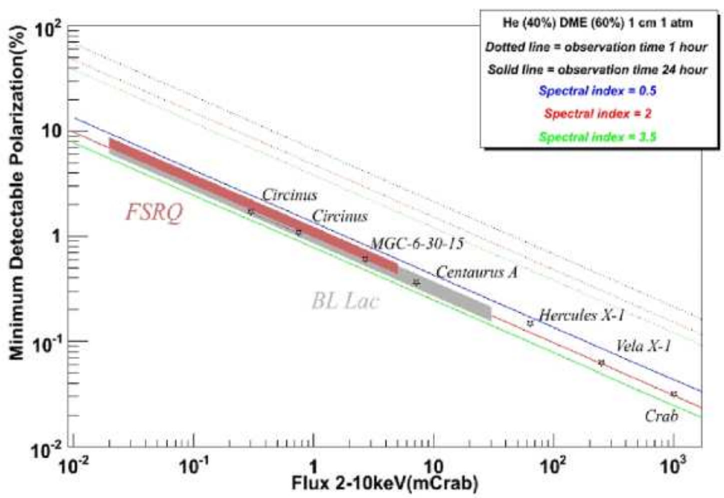


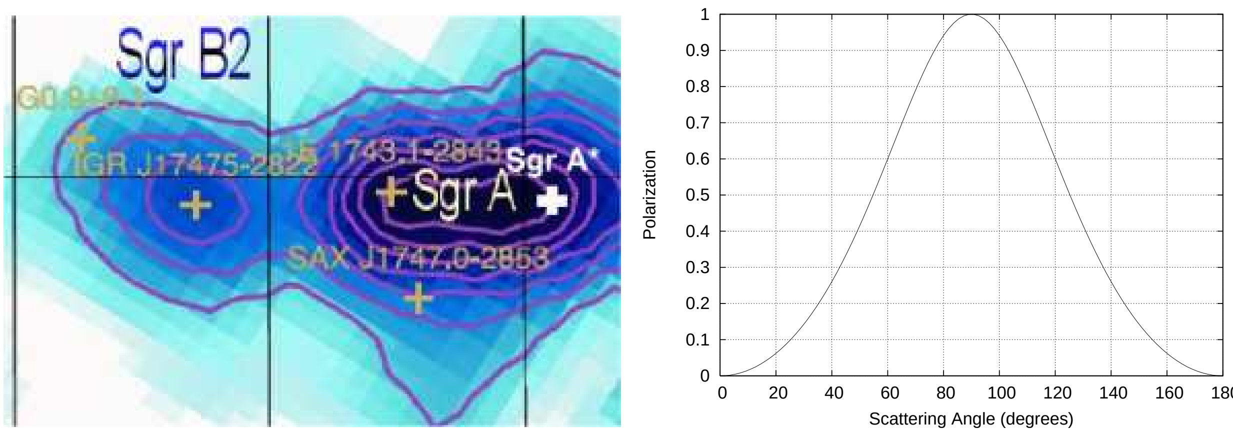
Figure 4. Minumum Detectable Polarization for XPOL. Very high sensitivity make XPOL to become the high throughput tool for X-ray Astronomy

Most of the characteristics typical of a front-end electronics are performed by the ASIC chip. Therefore the architecture will not require exotic solutions but will be mainly dedicated to configure and readout the data from the chip. The power consumption and the dimension therefore will be contained (see tab. 2).

The AD conversion will be performed at the maximum rate compatible with the ROI frame readout which at the moment is 10-20 Mhz. Pixel with no signal will be suppressed. Timing relies on the fact that the signal from the GEM is very fast and can be shaped by less than 1 μs without sensitive loss of signal. However most of the uncertainty is determined by the drift time in the gas which can be of the order of 1 μs. The overall accuracy will therefore be of $1.5 - 2\mu$s.

7.3. Sensitivity

The sensitivity of XEUS takes advantage of the large area and the good PSF. The contribution of the diffused X-ray background result therefore negligible down to the flux level for which polarization measurements are feasible in an observing time compatible with the planning of XEUS (10 μCrab). The internal (residual) background is expected to be very small. Particle background will be discriminated by the high granularity of the detector and by the fiducial sides. Compton electrons, releasing energy in the operative range of XPOL, are few because of the low atomic number of the gas exploited. In our calculation we conservatively do not apply any further background-rejection, even so the particle background is negligible.



(a) (b)

Figure 5. Panel (a) shows part of the Galactic Center region from the INTEGRAL observation.[6] The giant molecolar cloud Sgr B2 probably is reprocessing the X-ray radiation coming from Sgr-A* since 300-400 years. From the degree of polarization of scattered radiation (Panel (b)), one can estimate the angle of scattering and, thus, the correct distance of Sgr B2 from Sgr A*.

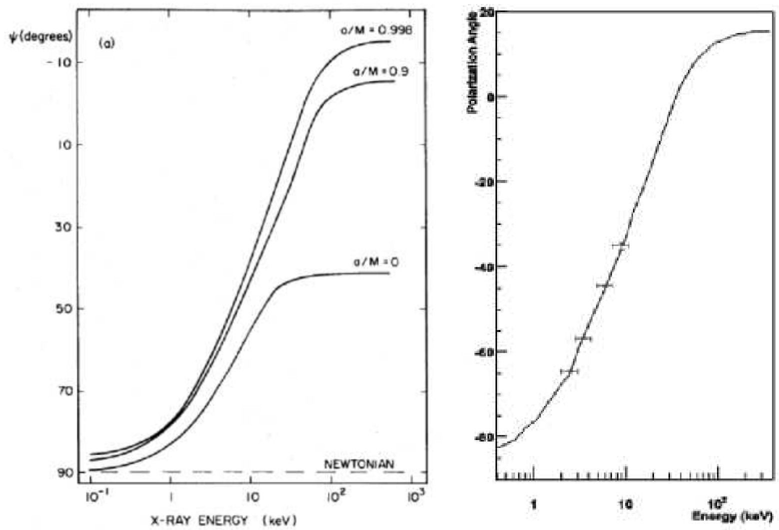
8. SOME GOALS FOR XPOL

8.1. Was The Milky way an AGN in the recent past?

The region around the Galactic Center is complex. There are molecular clouds for which is only known the projected distance respect to us. One of these molecolar clouds, Sgr B2, has been studied[7] in detail by ASCA and more recently by INTEGRAL.[6] The spectrum shows an iron line and a reflection component. Also it looks brighter on the direction of Sgr A* which is supposed to harbour a massive black hole. The prevalent (and old) hypothesys[8] is that Sgr B2 is reprocessing the radiation pervening from the central black hole. The latter was flaring 300-400 years ago which is the travelling time to Sgr B2. The measurement[9] of the degree and of the polarization angle will permit to confirm this hypothesis and to measure the real distance to the central BH providing an estimation of the luminosity of Galactic Center when it was a faint AGN in the past. In one day of observation of XPOL the MDP expected is 6.8 %.

8.2. Matter in extreme Magnetic fields: testing QED

The presence of magnetic fields of the order of 10^{13}, 10^{14} gauss in neutron stars such as Anomalous X-ray Pulsars or Soft Gamma Ray Repeater (SGR) are mainly derived on the base of energetic considerations. QED predicts that, at this large magnetic field value, the vacuum becomes birefringent and that the polarization degree from magnetized neutron star can assume a large value.[10,11] Due to the extreme magnetic field also two absorption features should be present, one at the so called vacuum resonance frequency, and one at the proton-cyclotron resonance.[12] These features should have different phenomenology with respect to polarization. This would provide a direct evidence of the presence of extreme magnetic fields and provide a check of the magnetar model. In an active phase or in the first few days following a major emission episode the situation may become even more interesting, because of the likely presence of a transient ionized atmosphere. The presence of a feature at 5 keV in the spectrum of SGR1806-20[13] has been explained as due to a proton cyclotron line.[14] The spectroscopic capability of the Micro Pattern Polarimeter allows to perform energy resolved polarimetry and test the QED predictions. The lack of QED effect on polarization would imply the presence of a red-shifted iron line which has deep implication in the determination of the Equation of State of the neutron stars.



(a) (b)

Figure 6. (a) Expected variation of the polarization angle with energy of the radiation coming from the accretion disk of a BH[16,17] (b) result of a simulated observation of 12 hours of Cyg X-1 where the plane of polarized (5%) radiation is rotated according to the prescription of (16). We can observe the rotation with a very high statistical significance (see text).

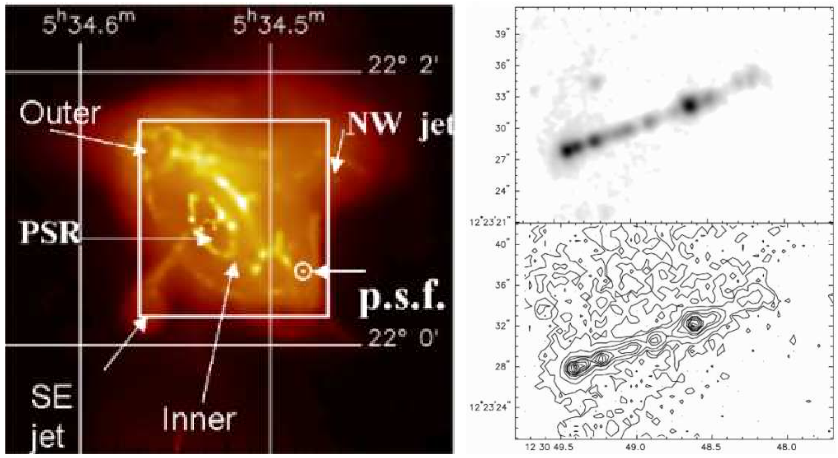
8.3. Matter under extreme Gravitational Fields: testing GR

Radiation emitted from the innermost region of an accretion disk can be polarized by means of scattering. At a distant observer, neglecting General Relativity (GR) effect, the polarization vector is parallel or perpendicular to the major axis of the projected disk on the sky.[15] In presence of a Black Hole in a soft-state the disk is optically thick and geometrically thin extending down in the vicinity of the BH, when GR is taken into account, a continuous rotation of the polarization vector with energy is expected[16,].[17] In fact photons more energetic are emitted closer to the BH and the rotation due to effect of GR is therefore larger.

We simulated an observation for Cyg X-1 in soft state of 12 hours with XEUS and in the input data (we supposed a polarization of 5 we rotated the plane of polarization according to the prescription of.[16] The results are shown in figure 6. Clearly the rotation is detected with a far high statistical significance. XPOL will be able therefore to detect such a variation either with a much less integration time (the error scale as $\sqrt{T}$) and with a lower intrinsic polarization of the source. More with good statistical significance would be possible to detect the momentum (maximally rotating/non rotating) of the BH.

8.4. Cosmic Accelerators: the prototype

Even if considered to be the calibration source of X-ray sky observatories, Crab Nebula continues to reserve many surprises (see fig. 7(a)) . When observed with the fine position resolution of Chandra,[18] many substructures are evident: an inner torus, an outer torus and two jets . The standard picture of the Crab Nebula was derived long ago by 19. Kennel and Coroniti assumed that a magnetohydrodynamic wind from the pulsar terminates in a shock and the post-shock shines in the synchrotron nebula. In their model the frozen magnetic field is supposed to be toroidal. However if this is the case the brightness around the torus will not be uniform in two opposite direction of the torus. The hypothesis that the magnetic field be, instead, turbulent resolves this discrepancy and can be probed by polarization angle measurements resolved in space which are possible with XPOL thanks to its spectral/imaging capability. By mapping the polarization angle on the Crab image will be possible to gather



(a) (b)

Figure 7. Crab Nebula Observed by Chandra (**a**) with overimposed the field of view (FOV) of XPOL, the PSF of the XEUS mirrors and, inside, the PSF of the polarimeter, **b** grey scale of the M87 jets (top) observed by Chandra and the brightness contour (bottom) with the core on the leftest brightest peak and the knots on the right.

information on the spatial structure of the magnetic field and on the physics of the interaction of the wind with the nebula.

8.5. Cosmic Accelerators: the jets

Jets in Blazars, radio galaxies and in Micro Quasars are the sites of acceleration of particle up to very high energies which can reach also TeV. In most of the cases the particles (leptons) can be responsible of the observed X-ray radiation. In Blazars low energy photons can be up-scattered by the same emitting electrons (Synchrotron Self-Compton) to X-rays or, conversely, the external UV photons from the disk can be Comptonized to X-rays. The polarization degree and angle with respect to other wavelengths is different for this two cases.[20,21] X-ray polarimetry therefore permits to disentangle between the two models establishing the origin of the emission, the role of the disk and the nature of the jet. In Radio Galaxies, like the FR I M87, and in the case of Micro Quasar XTE J1550-564 the Jet interacts with the ambient medium and forms bright knots at a distance from the central core. The X-ray coming from those knots can be resolved (see fig. 7(b)) and analyzed by XPOL to determine if the degree of polarization is compatible with a synchrotron origin. Conversely, if X-rays are generated by comptonization of external photons for example those deriving from Cosmic Microwave Background Radiation, the degree of polarization may be very small for the hysotropy of the source photons.

9. CONCLUSIONS

The advent of the Micro Pattern Gas Detector, a finely subdivided pixel gas chamber detector readout by large area and small pixel size CMOS ASIC allows to image the track of the photoelectron and derives the polarization of the X-ray photon together with energy position and time. XPOL, as auxiliary instrument at the focus of the large mirror area of XEUS telescope, will be decisive in many of the scientific goal of the mission being therefore the high throughput no more laking tool of X-ray Astronomy.

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